COMPACT BATTERY/CAPACITOR ELECTROMAGNETIC LAUNCHER TESTBED*

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ABSTRACT

A 0.4 megawatt per pound battery/capacitor system is a viable means to power a Small-Caliber Electromagnetic Launcher (SCEML). A SCEML test-bed is in operation at our Laboratory which uses a 55 pound, 0.9 kilojoule per kilogram electrolytic capacitor discharge sub-system and a demountable, compact SCEML that serves as the switch and load. A secondary battery sub-system that weighs 45 pounds has been designed to operate up to 1000 volts and is capable of charging the capacitors at a 1.0 Hertz repetition rate for a minimum of 100 cycles. The total battery/capacitor power system weight is 100 pounds.

Power conditioning experiments are in progress under railgun load conditions with a near-term objective of demonstrating a 100 pound power-conditioning system that is capable of powering a projectile of weight 2.0 to 4.0 grams with a muzzle velocity of 2.0 kilometers per second and with a barrel length less than 1.0 meter. Experimental data is presented; new higher-power, energy battery/capacitor power systems are highlighted; and future program plans and some important conclusions are discussed that give support to a compact, lightweight battery/capacitor power conditioning system for a SCEML.

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INTRODUCTION

Electromagnetic Launcher Systems have many components, however, the major ones are the power supply, switches, launcher, and projectile. At the Electronics Technology and Devices Laboratory (ETDL), we are concerned with the power supply, switching and the power conditioning required to deliver the energy to the EM Launcher with the proper pulse characteristics conducive to the application. In the switching arena, work is being done on spark gap and thyratron switches traditionally used for pulse-power applications. Also, semi-conductor and optically activated switch (OAS) programs are underway and have as a goal the development of a family of semiconductor power switches capable of operating over a wide range of specifications. This paper examines the power supply system, and in particular, a compact battery/capacitor system for a Small-Caliber Electromagnetic Launcher (SCEML). The SCEML Project is aimed at reducing size and weight of the prime-power source and pulse-energy store. A long term objective is to integrate the power source and the pulse-energy store into a compact power system demonstrator.

A comprehensive parametric study was conducted by the Center for Electromechanics at the University of Texas at Austin for Battelle Laboratories under contract to the U.S. Army Armament Research Development and Engineering Center (ARDEC) to determine the optimum power system for a SCEML to launch a lightweight (2-4 grams) projectile. The study concluded that an aircore compensated pulsed alternator (compulsator) was a feasible candidate for a vehicular mounted, SCEML. The study recommended the development of a compulsator for a SCEML capable of firing a 20 gram projectile at 2.5 kilometers per second (Km/sec) in either a salvo or rapid-fire mode. For lighter-weight projectiles in the 2 to 4 gram range, the compulsator becomes less attractive and a battery/capacitor system becomes a more viable candidate. The battery/capacitor power system uses a high-power density, secondary battery and a high-energy density electrolytic capacitor bank for energy storage. At ETDL, a SCEML Power Conditioning Program is underway that is aimed at producing the battery/capacitor power system with program objectives given in Table 1.

POWER SUPPLY ENERGY:	25 KILOJOULES
EFFICIENCY:	>12%
PEAK CURRENT:	200 KILOAMPERES
PEAK VOLTAGE:	<1000 VOLTS
PEAK POWER:	100 MEGAWATTS
PULSE DURATION:	1.0 MILLISECOND
TOTAL SYSTEM RESISTANCE:	<3 MILLIOHMS
POWER SYSTEM WEIGHT:	<100 POUNDS
REPETITION RATE:	1.0 HERTZ (NEAR TERM)
NO. OF CYCLES:	>100

TABLE 1: SCEML POWER CONDITIONING PROGRAM OBJECTIVES

SMALL-CALIBER EM LAUNCHER (SCEML)

The power conditioning experiments are conducted under railgun load conditions where a SCEML was designed to simulate an actual load and to allow rapid turn-around time between experiments. **Figure 1** is a picture of the demountable SCEML. The outer case is made of 0.5 inch thick aluminum with dimensions 3.4 by 4.0 by 14.5 inches. A total of 68 screws were added to mechanically strengthen the aluminum case against the large magnetic repulsive forces generated by current levels up to 200 kiloamperes (KA). The 18 inch gun barrel is used only to guide the projectile and does not have conducting rails inside. The two 15-inch long copper rails have a cross-sectional area of 0.5 by 0.625 square inches and are separated by 0.375 inch. Bakalite is used to electrically isolate the copper rails from the aluminum case. The backside of the aluminum case and the adjacent (rear) copper rail have holes to allow the projectile to be launched by a spring

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14. ABSTRACT
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loaded mechanism so that the projectile travels through the aluminum case and through the rear rail without making physical and electrical contact. The front rail has two sections that are separated by a gap of width equal to the armature width. When the armature makes contact with the front rail sections, it becomes a closing switch and current flows from the capacitor bank through the up stream front rail section, through the armature, through the downstream front rail section and thence through the rear rail back to the capacitor bank.

A detailed discussion of the principle of operation for the SCEML is beyond the scope of this paper.[1] Briefly, the large acceleration force on the armature is a combination of three effects. The predominant force factor is that caused by the thermoelectric plasma created by discharging the capacitor bank into the small volume behind the armature and in the gap between the two front rail sections.[2] The next important force factor contributor is the Lorentz force generated by the current passing through the armature. This force needs no further discussion since it is the magnetic force responsible for armature acceleration in the conventional, simple railgun. The third and least important force contributor is the magnetic-field reconnection, which takes place behind the projectile as it passes through the gap.[3] The rails of the SCEML have no current while the projectile is approaching. When the leading edge of the armature makes contact with the front rail sections, current flows through the rails. Current reaches its maximum or peak value as the armature transverses between the gap of the front rail. When the trailing edge of the armature begins to clear the inner edge of the rear rail, magnetic flux lines reconnect behind the projectile. The reconnected flux lines straighten to relieve their tension and propel the projectile. The magnetic-field reconnection effect is minimal for a lightweight armature of a few grams since the effective coupling is reduced.

Figure 2 shows time of flight data inside the barrel for SCEML 101 with a 0.5 gram projectile. The data was taken on a Tektronix Digital Waveform Analyzer System. The time was measured by using three laser beams separated by 0.15 meters. The average velocity inside the barrel of 1.905 Km/sec is in excellent agreement with the measured value of 1.912 Km/sec from a ballistic pendulum. The peak current was 143 KA and the capacitor voltage was 520 volts (V). The velocity data for SCEML 101 correlates with that of SCEML 103 which gave a velocity of 484 m/sec. for a 1.8 gram projectile, 140 KA peak current and 500 V operation. The acceleration of the projectile is over 400,000 G's.

HIGH-ENERGY DENSITY ELECTROLYTIC CAPACITOR BANK

An investigation was conducted into various types of capacitors such as electrolytic, double-layer bipolar electrolytic and impregnated metalized film. In choosing the preferred capacitor for a compact, high-energy density capacitor bank, many issues must be considered. The interfacing of the bank with other circuit components, the electrical configuration of the bank, discharge time, current pulse shape, voltage operation, equivalent series resistance (ESR) and cost are some important issues. The electrolytic type capacitor is currently incorporated into the SCEML testbed and all the experimental SCEML data presented below is for this type of capacitor. However, the double-layer bipolar electrolytic and the impregnated metalized-film capacitor are viable alternatives, and as such, information on these capacitors are also given below.

Table 2 is a comparison and a near term projection for the aluminum electrolytic capacitor.

	OFF-THE SHELF*	SPECIAL ORDER*	18 MONTH DEVELOPMENT
CAPACITANCE (FARADS)	0.1	0.02	0.021 (.0105)**
VOLTAGE (VOLTS)	75	200	275
ENERGY PER CAP. (JOULES)	281	400	800 (400)**
JOULES PER POUND	94	180	360
JOULES/CUBIC INCH	4.6	9.6	19.3
DIAMETER (INCHES)	3	3	3
HEIGHT (INCHES)	8.625	5.875	5.875 (2.938)**
WEIGHT	3.25	2.25	2.25 (LBS.) (1.125)**
EQUIV. SERIES RES. (MILLIOHMS)	4	4	UNKNOWN***
INDUCTANCE (NANOHENRIES)	23 - 28	23 - 28	10 - 15

*CAPACITORS ARE IN-HOUSE **OPTIONAL PACKAGING
***ESR MAY IMPROVE, BUT UNKNOWN

TABLE 2: ELECTROLYTIC CAPACITOR COMPARISON/PROJECTION

The electrolytic capacitor, that was a special order, is incorporated in the SCEML testbed. In a 50% (300 V) over-voltage condition, this capacitor has given a specific energy of 408 joules per pound (J/lb) which is greater than the 360 J/lb projected capacitor when operated at the rated voltage. The stress and operating life effects on the capacitor, in the 50% over-voltage condition, has not been determined by the author. It is suspected that a few hundred cycles can be achieved if the capacitors are discharged within a few seconds when fully charged. The capacitor was voltage stressed to 325 V (62% overvoltage) before the vent cap popped. As such, 300 V operation is perhaps too close to the safety limit and will adversely effect the capacitor life. **Figures 3 and 4** show data taken on a single capacitor tested at the normal 204 V operating condition and the 291 V (46%) over-voltage condition. The capacitor can weighs 1.0 kilogram.

A bank was assembled with twenty-four of the specially ordered electrolytic capacitors. Two sets of twelve capacitors are in series and the capacitors of each set are in parallel. The normal operating voltage of the bank is 400 volts. A picture of the capacitor bank is shown in **Figure 5.** The total weight of the bank is about 55 pounds and the volume is 0.74 cubic feet. The capacitor bank was evaluated at the 420 volts (normal voltage), 520 volts (25% over-voltage) and 592 volts (50% over-voltage) operating conditions. **Figures 6, 7 and 8** show theoretical and experimental comparisons of discharged voltage, current, power and energy for the above three voltage conditions. The theoretical energy is $1/2\ CV^2$ and the experimental energy value is the current and voltage integrated over the discharge time. For 592 volts (50% over-voltage) operation, the capacitor bank is discharging 178 KA of peak current over a 0.3 millisecond time period. The peak power is 72 megawatts (MW) and the energy is 18.4 kilojoules (KJ) with 56% of the energy delivered to the load. The total system resistance is about 3.0 milliohms. The bank contributes about 1.0 milliohm and the connectors and rails contribute the remaining 2.0 milliohms. The capacitance was measured for each capacitor, and the average capacitance is 0.018 Farads (F). The total bank capacitance is 0.105 F. The inductance was measured for each capacitor and the rails. The inductance is 0.11 microhenries. A Pearson current probe was utilized to measure the current.

BIPOLAR DOUBLE-LAYER ELECTROLYTIC CAPACITOR BANK

The bipolar, double-layer electrolytic capacitor consists of a stack of parallel plates seperated by an electrolyte in which a very large charge is stored on the plate surface in a thin surface layer of mixed metal oxides. The metal oxides have a very high effective surface area which gives a large charge storage capacity and current density. The electrolyte gap affects internal resistance, volume, current risetime and cell voltage. For an aqueous electrolyte, the cell voltage is about 1.2 volts and is fixed by the water breakdown limit. The metal substrate affects current density and volume. The cell dimensions (area) affect total current and internal resistance. For voltage operation higher than 1.2 volts, the cells are stacked in series. An important characteristic of the bipolar nature of the capacitor is that it can be rep-rated and withstand a reverse (ringing) voltage.

Tables 3 and 4 give capacitor characteristics for 10 and 85 volt capacitors built and tested by Pinnacle Research Institute (PRI), Cupertino, CA.

VOLTAGE:	10 VOLTS
CAPACITANCE:	0.1 FARADS
ENERGY:	5 JOULES
SPECIFIC ENERGY:	0.5 KJ/KG
ENERGY DENSITY:	1 J/CC
CURRENT DENSITY:	25 A/CM^2
EQUIV. SERIES RESISTANCE:	0.4 OHMS
INDUCTANCE:	<2 NANOHENRIES
PEAK CURRENT PULSED:	17 A
VOLUME:	5 CC (0.3 IN^3)
WEIGHT:	10 G (0.35 OZ)

TABLE 3: PRI 10-VOLT BIPOLAR, DOUBLE-LAYER ELECTROLYTIC CAPACITOR

VOLTAGE:	85 VOLTS
CAPACITANCE:	0.5 FARADS
ENERGY:	1.8 KJ
SPECIFIC ENERGY:	7 KJ/KG
ENERGY DENSITY:	20 J/CC
CURRENT DENSITY:	27 A/CM^2
EQUIV. SERIES RESISTANCE:	50 MILLIOHMS
INDUCTANCE:	<2 NANOHENRIES
PEAK POWER:	35 KW
VOLUME:	180 CC (11 IN^3)
WEIGHT:	300 G (0.7 LBS)

TABLE 4: PRI 85-VOLT BIPOLAR, DOUBLE LAYER, ELECTROLYTIC CAPACITOR

The data for the PRI capacitors given in tables 3 and 4 are for capacitors that do not have optimized packages. For the author's particular application of utilizing a capacitor bank to power a SCEML, the equivalent series resistance (ESR) of the capacitor is an important consideration. One would desire the ESR to be as low as possible. The 50-millohm value for the 85 V capacitor is larger than desirable for the SCEML application. However, a larger diameter cell plus a smaller seperation distance could reduce the ESR by an order of magnitude and make this capacitor an attractive energy store for the SCEML. The extremely large energy-density (20 J/cc) yields a compact capacitor bank.

Figures 9 through 12 give theoretical comparisons of the electrolytic capacitor bank (current bank) with a PRI capacitor bank at various capacitor bank resistances and for voltage, current, power and energy. The current bank weighs 55 pounds and consists of 24 capacitors. The 3 milliohm resistance is a total system resistance in which 1 milliohm is the capacitor bank resistance and 2 milliohms is the resistance of other circuit components. The four remaining curves on each graph is for a PRI type capacitor bank that would weigh 18 pounds and consist of 25 capacitors. The resistances given for the PRI capacitor curves are also total system resistances with 2 milliohms for other circuit components and the remaining resistance for the capacitor bank. The 52 milliohm curve represents the current state-of-the-art of the PRI capacitor. An order of magnitude reduction in ESR to 5 milliohms, would produce higher peak and average current and power, and much more energy than the currently used capacitor bank in the SCEML. The weight and volume reduction is two-thirds.

METALIZED-FILM CAPACITOR BANK

Impregnated metalized-film capacitors can also achieve high energy densities by using high dielectric constant (ϵ>10) films such as polyvinylidene diflouride. A capacitor bank, for the SCEML application, should be capable of operating over a voltage range of 400 to 1000 volts. This could be accomplished by utilizing capacitor modules to achieve the desired output voltage and energy. The voltage stress level, for these type capacitors, is an important consideration for operation under pulsed charged and discharged conditions. Metalized-film capacitors use one film between electrodes, and most breakdowns are accompanied by a self-healing effect. This causes loss in capacitance which must be minimized for high-voltage stress operation.

Table 5 gives characteristics for a proposed capacitor bank using impregnated metalized-film capacitors that have polyvinylidene diflouride film. The design data in Table 5 was obtained from the Dielectrics and Insulation Department at Westinghouse Electric Corporation R&D Center in Pittsburgh, Pennsylvania. One very attractive feature of this capacitor bank is the 0.01 milliohm internal resistance. The very low resistance would allow large peak current and power. The 1.0 KJ/Kg specific energy is a respectable value and probably could be further increased by R&D to decrease dielectric thickness and/or increase the dielectric constant.

VOLTAGE:	1000 VOLTS
CAPACITANCE:	0.05 FARADS
ENERGY:	25 KJ
SPECIFIC ENERGY:	1.0 KJ/KG
EQUIVALENT SERIES RESISTANCE:	0.01 MILLIOHMS
TOTAL WEIGHT:	25 KG (55 LBS)
TOTAL VOLUME:	1.5 FT^3

TABLE 5: PROPOSED WESTINGHOUSE 1000-VOLT METALIZED-FILM CAPACITOR BANK

SECONDARY BATTERY SUB-SYSTEM

A secondary silver oxide-iron battery subsystem has been proposed which would operate up to 1000 volts. The battery sub-system weighs 42 pounds, is sized for high power and is capable of fully charging the capacitor bank to full voltage at a 1.0 Hertz (Hz) repetition rate and for a minimum of 100 cycles, after which the battery is fully discharged. The silver oxide-iron battery was chosen rather than silver oxide-zinc because it is rugged, stable and can give long operating and shelf lives. **Table 6** gives the battery design objectives for a Westinghouse silver oxide-iron battery. The model that they used to obtain the design data was a finite element model which takes into account the load profile imposed by the RC circuit, the limiting current imposed by solid state diffusion rates, and known properties of the battery materials.

NUMBER OF SHOTS:	>100
VOLTAGE:	1000 VOLTS
ENERGY PER SHOT:	25 KJ
SPECIFIC ENERGY:	130 KJ/KG
TOTAL ENERGY:	692 WATT-HOURS
SPECIFIC POWER:	1.3 KW/KG
DISCHARGE TIME:	1 SECOND
TOTAL WEIGHT:	19 KG (42 LBS)
TOTAL VOLUME:	0.6 FT^3

TABLE 6: PROPOSED WESTINGHOUSE SILVER OXIDE-IRON BATTERY SUBSYSTEM

CONCLUSIONS

A 0.4 megawatt per pound battery/capacitor system has been described that uses a high-energy density electrolytic capacitor bank that weighs 55 pounds and a silver oxide-iron battery that weighs 42 pounds, for a combined weight of less than 100 pounds. Experimental data was given for the electrolytic capacitor bank that demonstrated 178 KA of peak current, 72 MW of peak power and 18 kilojoules of energy discharged over a 0.3 millisecond time period. The capacitor bank was operated up to a 50% (600 V) over-voltage condition yielding a 0.9 KJ/Kg specific energy. Design data was given for a silver oxide-iron battery that operates at 1000 volts with a 1.0 Hz rep-rate and allows a minimum of 100, 25 KJ shots before recharging. Also, data was presented for a new, promising bipolar double-layer electrolytic capacitor and an impregnated metalized-film capacitor. The bipolar, electrolytic capacitor is attractive because of the very high-energy density, and the metalized-film capacitor is attractive because of the low ESR in conjunction with a respectable energy density.

Future plans are to integrate the prime power source with the energy store to produce a power pack which meets the objectives as given in Table 1. These objectives could be met with a modest level, two year developmental program. A five year projection for the power pack could surpass the Table 1 objectives by increasing the rep-rate to 5 Hz and decreasing the power pack weight in half.

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3. M. Gowan, E. C. Cnare, B. W. Duggin, R. J. Kaye and T. J. Tucker, "The Reconnection Gun," 3rd Symposium on Electromagnetic Launch Technology, April 86, PP 25-30.

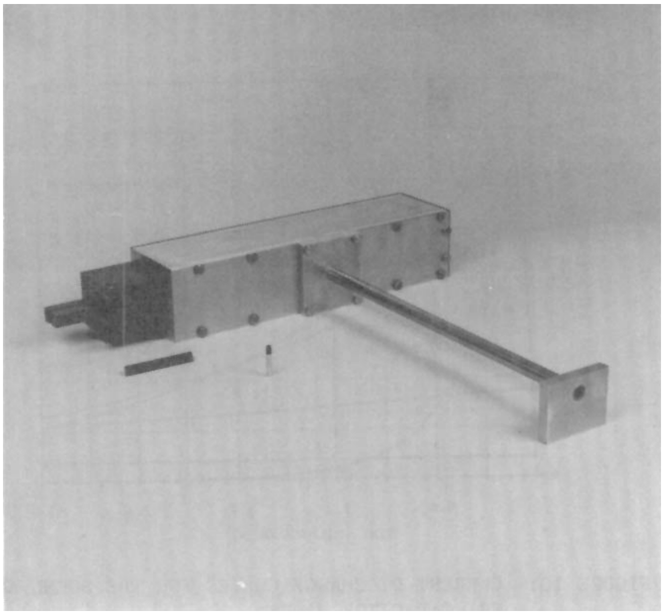

FIGURE 1: SMALL-CALIBER ELECTROMAGNETIC LAUNCHER (SCEML)

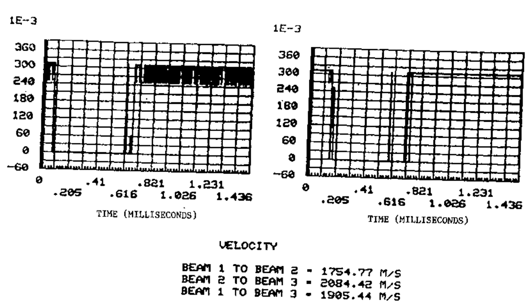

FIGURE 2: PROJECTILE TIME OF FLIGHT INSIDE SCEML BARREL

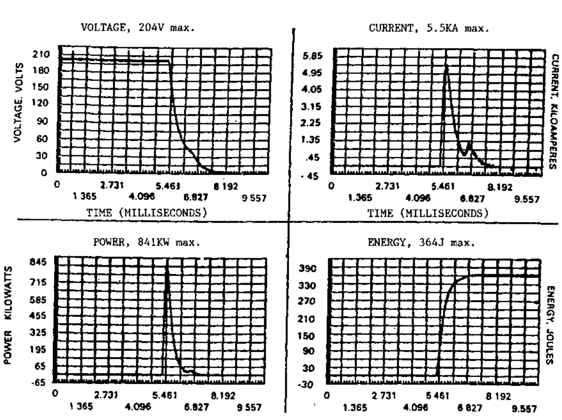

FIGURE 3: DISCHARGE CHARACTERISTICS OF ELECTROLYTIC CAPACITOR AT 204 VOLTS

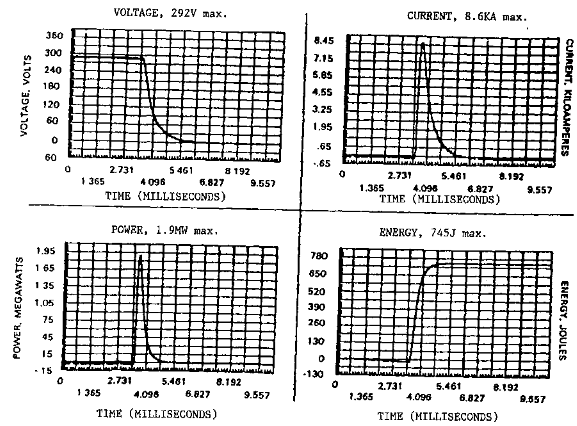

FIGURE 4: DISCHARGE CHARACTERISTICS OF ELECTROLYTIC CAPACITOR AT 292 VOLTS

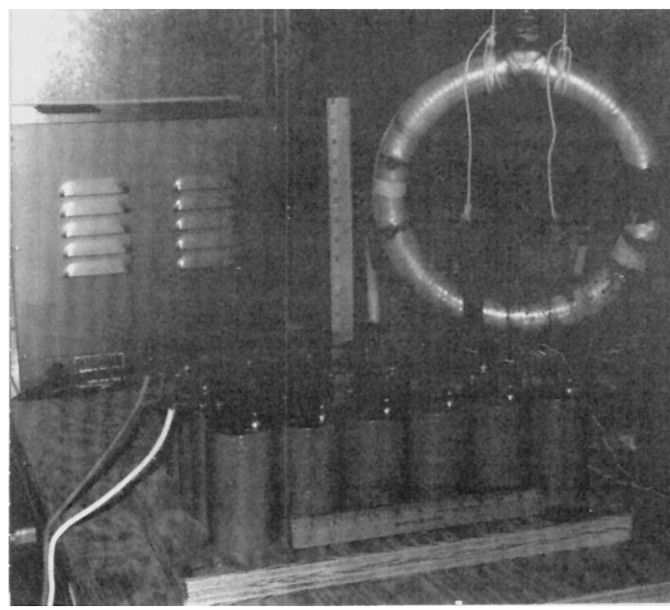

FIGURE 5: SMALL-CALIBER ELECTROMAGNETIC LAUNCHER CAPACITOR BANK

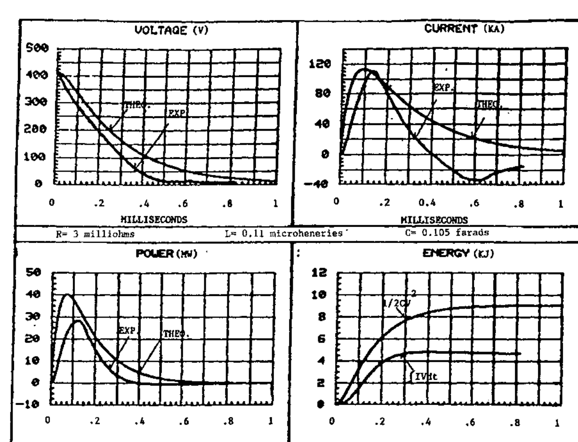

FIGURE 6: SCEML CAPACITOR BANK THEORETICAL AND EXPERIMENTAL DATA AT 420 VOLTS

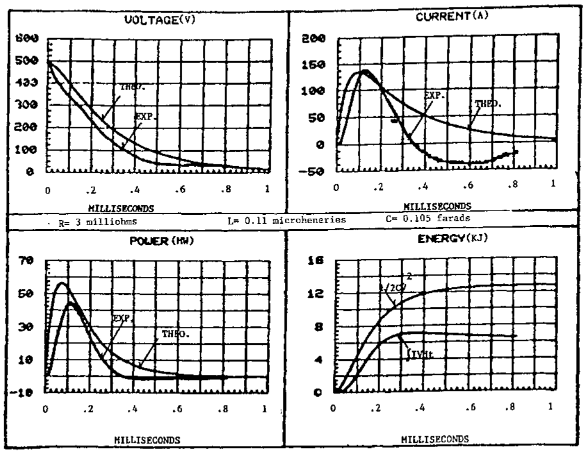

FIGURE 7: SCEML CAPACITOR BANK THEORETICAL AND EXPERIMENTAL DATA AT 520 VOLTS

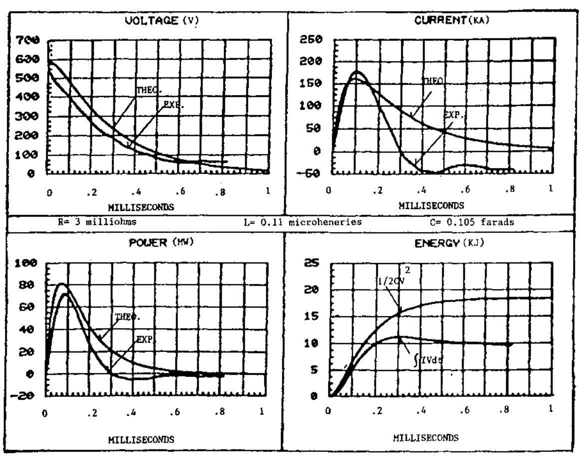

FIGURE 8: SCEML CAPACITOR BANK THEORETICAL AND EXPERIMENTAL DATA AT 592 VOLTS

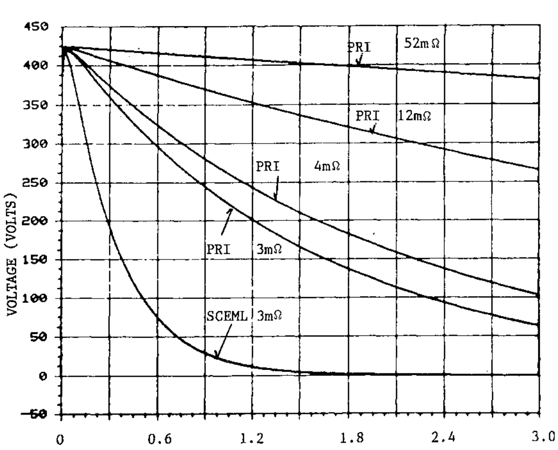

FIGURE 9: VOLTAGE DISCHARGE CURVES FOR THE SCEML AND PRI CAPACITOR BANKS

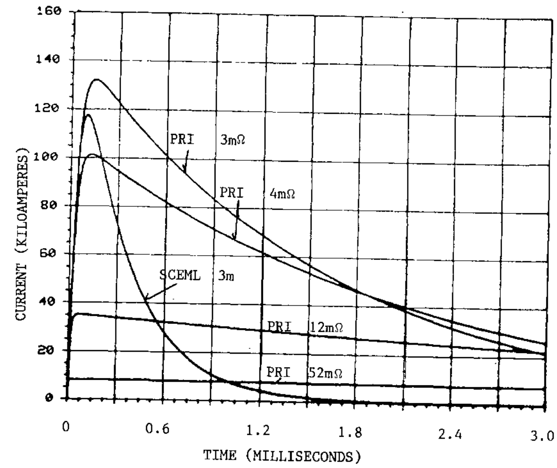

FIGURE 10: CURRENT DISCHARGE CURVES FOR THE SCEML AND PRI CAPACITOR BANKS

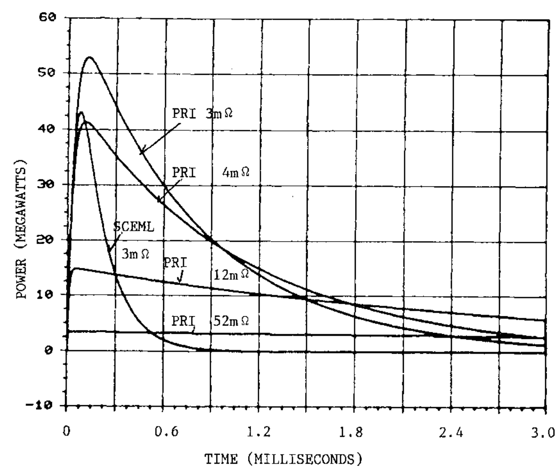

FIGURE 11: POWER CURVES FOR THE SCEML AND PRI CAPACITOR BANKS

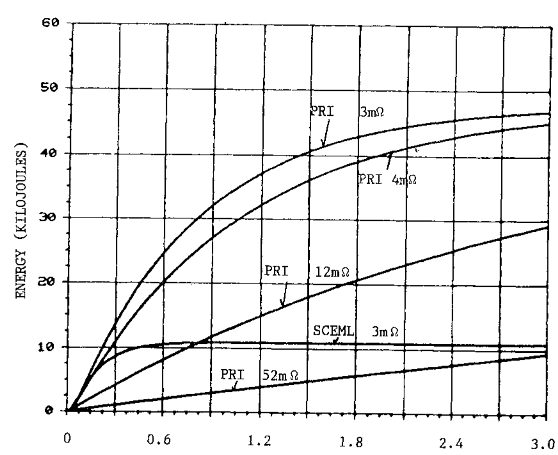

FIGURE 12: ENERGY CURVES FOR THE SCEML AND PRI CAPACITOR BANKS